Enhancement of Performance for Grid Connected Solar PV with PLL in distorted Grid Conditions

SHORT SYNOPSIS

Submitted in partial fulfillment of the requirement of the degree of

DOCTOR OF PHILOSOPHY

by

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I hereby declare that the short synopsis entitled **Performance Improvement of Solar PV Grid connected System using PLL under Grid Disturbances** being submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in the Department of **Electronics and Communication Engineering under** the **School of Engineering of** Manav Rachna University, Faridabad during the academic year **2025-26.**

It is the work that is expected to be carried out under the supervision of **Dr. Shruti Vashist** and co-supervision of **Dr. Sumit Saroha** Further, it is declared that the short synopsis is within the plagiarism limit and copy of the same is attached as per the University norms.

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ABSTRACT

Currently, the integration of solar photovoltaic (PV) based generation systems with electrical grid is very important for expanding the use of renewable energy (RE) based generation system. One of the most critical components of this process is to achieve precise synchronization between solar PV inverter output with grid to ensure stable and efficient energy transfer. The Phase-Locked Loop (PLL) techniques are widely used for this purpose, as they enable continuous alignment of the inverter's output with grid's voltage, frequency and phase. This present research is focused on implementation of grid synchronization using the PLL technique by emphasizing on operational flow and key components.

As per existing literature, number of PLL techniques such as: Synchronous Reference Frame PLL (SRF-PLL), Second Order Generalized Integrator (SOGI) based PLL, Third Order Generalized Integrator (TOGI) based PLL and other enhanced PLL have already been proposed by number of researchers and their performance is also tested under non ideal grid conditions like: "voltage sags & swells, frequency variations, DC offset and harmonic distortions". The improvement in performance has been validated through improved dynamic response via transient parameters like: "rise time, settling time, peak time, overshoot and peak phase error" etc. The process of synchronization also includes the continuous monitoring of grid conditions to maintain stability and reliability. This enables the efficient injection of solar power into the grid even under fluctuations in grid either from grid side or load side.

In this thesis, novel enhanced PLL based synchronization method is proposed to ensure the robust and reliable solar PV grid integration which would further contributes to improvement in grid stability and power quality via renewable energy adoption. For the analysis of results, the simulation process is carried out in Matlab. The improved dynamic response obtained through simulations and analysis in terms of above-mentioned transient parameters will reveal the superiority of proposed controller.

Key Words: Grid Disturbances, Phase Lock Loop, SOGI, Solar PV Integration, Synchronization

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1. Introduction

As per global electricity review report 2024, the electricity demand will grow around 3.3 percent i.e. 968 TWh which is higher than as compared to the growth of 2.2 percent (+627 TWh) for 2023. On the other hand, last 10 year average growth of electricity demand was 2.5 percent per year and it would increase by nearly twofold by the end of year 2050.The traditional used fossil fuels for generating electricity are unsuitable as they pollute the environment due to release of various harmful gases such as greenhouse gases. Therefore, every nation is trying to meet their growing demand using clean energy i.e. solar along with wind power plays a crucial role to meet this growing demand. In 2023, the solar capacity additions was 74 percent which is higher than the growth of year 2022 and wind capacity addition was 47 percent higher as compared to year 2022. The combined generation with the help of clean power using solar & wind was around 930 TWh at typical load factors and this growth of clean generation as per the forecast for year 2024 may leads to fall in emissions due to power sector. In the coming years, the energy capacity of solar & wind is expected to be reached at triple of its capacity as compared to 2023 level. This increased capacity will be sufficient to offset the emissions which is the result of growth in power sector demand. [1][2].

Among the clean energy sources, the electricity generated with the help of solar PV systems is one of most promising sources. Owing to its environmentally friendly nature, less establishing cost and easy installation, makes PVs a sustainable energy source. Viability and sustainability nature associated with it has improved its potential to get integrated into the electricity supply network, for example, grid. This dual combination is a remarkable step for achieving sustainable development. Sustainable energy from the sun can be sourced by employing two ways. First by combining the thermal energy inputs with the solar energy and the second one to integrate or harness the solar energy using PV modules. Both these harnessing techniques have different working principles. The former is solely based on the thermal process and employs energy demanding conversion while as in the later the PV cell directly converts sunlight/sunrays into electricity. In PV-enabled system the amount of solar energy converted on different environmental and module setup factors. Now what is offered if the solar PV is integrated with the grid system. Well, this integration caters various benefits ranging from reduction in emission of greenhouse gases, improving energy security and generation of clean and uninterrupted power supply. However, there are certain

challenges including stability, system efficiency, economic and regulatory issues that have to be mitigated to make this system more efficient. Therefore, to harmonize and maintain a constant synchronization in the grid system, there is requirement of precise control over solar PV system to integrate it with grid. The synchronization alignment of 'voltage, frequency & phase' of solar PV output power with grid will improve power productivity and this address the cleaner energy demand. The synchronization process will ensure that the electricity generated and injected into grid, is safe and efficient. The key parameters that must be taken into consideration at the time of synchronization are as discussed below:

1. **Voltage Magnitude**: The magnitude of voltage generated by solar PV and grid should be equal in order to prevent any potential damage to the equipment.
2. **Frequency**: The frequency of grid and generated voltage of solar PV must be same, typically 50 or 60 Hz depending on the region.
3. **Phase Angle**: The phase angle of solar PV output must be synchronized with the grid phase angle to transfer the seamless power at load end.

These are the following benefits of Solar PV integration:

1. **Impact on Environment:** The proposed Solar PV based electricity generation system generate electricity without emitting greenhouse gases by reducing the carbon footprint in the sector of energy emission. Hence, it is very critical part of integration to reduce air pollution and in combination with climate change parameters.

2. **Energy Security**: The diversity in fuel mix with the help of solar PV system will reduce dependence on fossil fuels-based generation which enhances the energy security of the system. This diverse energy-based generation system will help in protecting the system against supply disruptions which will further results in volatility of prices of fuel.

3. **Economic Benefits:** The use of solar PV systems for electricity generation will reduce the electricity costs for consumers through feed-in tariffs and net metering mechanism. Further, there are possibilities of additional jobs in design, manufacturing, installation, maintenance and research etc.

4. **Grid Resilience:** This attribute can be achieved during the peak hours by reducing the load through central power system management using transmission system.

There are certain challenges associated with Solar PV Grid Integration using proposed PLLs. Among them weak grids are the recurrent challenges in managing and maintain uniform load output. Weak grids are the major contributors to short circuit ratios. This causes an instability issues with the grid system. Under such conditions conventional PLL systems fail to maintain synchronization. Thus, it leads to voltage flicker and reduced power quality. Another challenge is harmonics and distorted voltages. These imbalances put negative impact on the power quality by reducing the sensitivity and the specificity. It has been observed that the use of SOGI based PLL and other adaptive PLL's have mitigated these changes. Another major challenge is variation in frequency. At times, the power supply faces significant variations in frequency. The conventional PLLs often fail to detect or track them accurately. Hence the need of adaptive PLLs is warranted. Likewise grid faults, like voltage sags or swells, can disrupt the operation of PLLs can cause the synchronization loss. The advanced PLL design strategy needs to incorporate fault- tolerant mechanisms for ensuring the continuous operation during variations in frequency and phase.

2. Literature Review

This literature review highlights the critical aspects associated with PLLs in solar PV grid integration and the continuous evolution of these technologies to meet the demands of modern power systems. As this field evolves new theories and algorithms get developed. For instance, Kanwar et.al [3] developed an improved PLL (IPLL) based control theory that tendencies to mitigate Solar PV grid-integration (SPGI) issues. In this concept the feedback signal of the distorted load current has direct control of converter pulses under these conditions. Thus, load output is controlled under unbalanced distorted grid. The proposed PLL scheme control the dynamics of SPGI by incorporating DC-link and grid voltages. Additionally, the in-phase load current components estimate reference value of grid current. This way IPLL uses maximum power from grid connected solar PV (GCSPV) and hence, there is improvement in power quality. A widely used three phases based PLL have been used like SRF-PLL or DSOGI-PLL, which have demonstrated a satisfactory output. Though they have some decoupling issues, thy tend to perform well to unbalanced faults when combined with hybrid PLL system.

Hemant Saxena et.al [4] developed new algorithm based on hybrid and modified system. This algorithm works by combining frequency locked loop and zero crossing detector. The system extracts the phase angle & frequency signals for synchronization. This improved system showed improved efficacies under distortions when tested in real time scenario. The achieved vales of THD were achieved almost close to zero.

Saptaparna et.al [5] conducted a study wherein he used low voltage ride through for GCSPV. Using this system in GCSPV, it has been observed that during the fault level, the quadrature axis current increased with respect to augmented current generated by Solar PV. Thus, to ensure the inverter's safe operation, SRF based PLL was designed using mathematical modeling. The designed PLL has adjusted the direct axis current (Id) for limiting the inverter current within acceptable range. The results reaffirm that these current control strategies are effective in nature. Even at fault time, this control strategy puts the limit on spikes of inverter current between 20-25%.

Anton et.al [6] modeled non-linear analysis based SRF-PLL. This system was generated with an aim to handle the oscillations in three phase voltage. As we are aware that

the feedback control loop is one of the most common structures in PLL. However, it a known fact that this loop gets effected under varying level of frequencies. Normally such deterioration happens owing to poor filtering and because of using nonlinear loads. Saravana et.al [7] tried to address these limitations by proposing a novel PLL technique. The proposed PLL extracted the harmonic current without the use of phase detector and oscillator. The outcomes were low value overshoot, settling time and computational time. The evaluated results in terms of low value of overshoot, settling time and computational time shows the efficacy of proposed PLL. The conventional PLL's generally used the signals of amplitude in terms of sine and cosine waves. All the evaluations are performed in the presence of dynamic grid condition of frequency jump, phase angle jump, voltage dip and third harmonics etc.

The integration of multiple energy sources (along with renewable energy) based generating unit with grids and use of nonlinear loads at large-scale introduces multiple challenges for synchronization of grid. Whereas, commonly used PLL based techniques are not very efficient one to tract the exacted grid signal components specifically in the presence of unbalances. To handle these challenges, Jian-hong Zhu et.al [8] deployed dual-layer filtering (DLF) along with PLL to improve the accuracy of grid synchronization parameters in presence of said unbalances. The DLF structure composed of cascaded delay signal cancellation (CDSC) circuit for enhancing structure of MSTOGI which is deployed to abolish the interference caused by unbalances. The achieved phase accuracy of 99.5% confirms the effectiveness of proposed technique used.

Zhang Taoet.al [9] has resolved one of the common complex single phase power grids problems which is associated with micro-grid. The system is tested in the presence of variations in frequency components along with harmonics. The proposed PLL technique is working on the basis of inverse Park transform (IPT) for conversion of signal into the converters. In the first (detection) stage, α component which is output of Park transformation is utilized as reference then, orthogonal signal is 1/4 of fundamental period using delay. For addressing the errors in delay arise due to frequency variations, the Lagrange interpolation polynomials has been introduced. For the suppression of low-order harmonics instead of PI controller's there is addition of resonant based controllers. At the end, results through experimental analysis demonstrate that proposed IPT based PLL offers its ability to handle variations in complex power strongly. Hence, proposed approach exhibits excellent dynamic

as well as static performance by improving the grid side signal frequency tracking performance, suppresses low-order harmonics and DC bias interference.

Sabisha Sureshbabu et.al [10] has highlighted the growing market of solar PV based electricity generation system and its utilization for integration into the grid is very essential. In this paper, a novel SRF based PLL control algorithm is deployed for three-phase (single stage) GCSPV. In the proposed model the GCSPV is integrated with PV and a three-phase single stage inverter with a filter component. To maintain a constant synchronization with grid voltage the output volume was regulated with SRF-PLL. The LCL filter maintained the high-frequency harmonics. The proposed control strategies demonstrated significant effectiveness in voltage regulation and synchronization.

The SOGI based PLL is a dominant technique for single phase application. This feature is particularly adaptive to varying frequency levels. As abnormal and unstructured current usage causes nonlinearity in loop at coupling stage, this results in degradation in performance, especially during grid frequency variations in the presence of unbalances. Jinming et.al [11] tried to address these limitations by proposing frequency-fixed SOGI based PLL. The said PLL has effectively eliminate the estimation errors under aforesaid frequency disturbances. The negative resistance behavior of PLL is also one of the factors behind the degradation of system's stability.

Unbalances in load current impacts the efficiency of SRF-PLL. This is mainly because of frequency, phase angle and voltage magnitude. Hence it is prudent to explore more research and generate novel and advanced techniques or algorithms that addresses these issues. Consequently, more researchers have to work to explore the more advanced PLL techniques. Among these, the Dual TOGI- PLL alongside Quasi-Type-1 PLL (QT1-PLL) have gained attention to improve the efficiency of conventional PLL. The said techniques have their respective strengths and weaknesses corresponding to the application. Therefore, there is utilization of combined hybrid technique which took the advantages of both techniques to outperform for grid synchronization issue. The proposed hybrid PLL firstly incorporates DTOGI adaptive nature filtering and then secondly incorporates QT1-PLL rapid transient response. The experimental results through MATLAB simulink environment validate usefulness of said PLL in the presence of challenging grid conditions as compared to

individual performance of both aforesaid PLL performance [12].

For three-phase SRF-PLL, designing process of sequence separator is very complex task at pre-filtering stage. To deal with this challenge, traditionally, SRF-PLL and pre-filtering stages used as an independent system. So, this work emphasized on designing a systematic and efficient approach for control parameters of SRF-PLL with pre-filtering capabilities. Initially, in pre-filtering stage the sequence components have been detected then minimizing the interaction between the pre-filtering stages with SRF-PLL. This can be achieved by using a derivative-filtered PID controller in place of conventional PI as the loop filter. The extensive experimental results confirm the effectiveness of proposed technique, demonstrating its applicability in improvement of SRF-PLL performance [13].

In SOGI-PLL, the tracking frequency from PLL is fed back into front end working as an input to SOGI to create frequency-adaptive SOGI base PLL. This technique is quite complex at implementation stage which also increase the tuning sensitivity along with reduction in stability. Therefore, in order to address these challenges, FFSOGI-PLL has been designed not only to ensure stability but also simplify its execution procedure. During its implementation it is observed that in the FFSOGI has produced difference in amplitude due to presence of frequency drifts. These frequency shifts actually cause the change of in-phase amplitude along with quadrature-phase signals. These shifts produce ripples of second order harmonic that results in inefficient parameters estimation. So, to handle this, small-signal model of said PLL is implemented and validated experimentally [14].

The Synchronverter (SV) control is widely used for distributed energy resources (DERs) due to its ability to adjust itself according to the behavior synchronous generator. But, under unbalance in grid, there is requirement to integrate more control strategy (control order PLL block) to achieve the ripple-free power into the SV control. Therefore, enhanced PLL (EPLL) structure has been utilized comprising of individual control for positive, negative, and zero sequence. This integration helps in DERs to inject power into an unbalanced grid without double-frequency components. The SV and EPLL both operate in natural frame of reference under unbalance in grid [15].

Surya Prakash et.al [16] introduced Type-3 SOGI-PLL control algorithm for single-phase systems which offers a very fast dynamic response. However, during disturbances in

grid cause oscillations into fundamental frequency. Generally, filters are used to suppress frequency oscillations caused by DC offset but, filters can reduce bandwidth of PLL which have negative impact on its dynamic response by introducing a delay in phase. Therefore, the article proposed a Modified Notch-Filter (MNF) based Type-3 SOGI for the elimination of phase error without compromising its dynamic response with frequency-adaptive control. For checking the effectiveness of proposed algorithm, results are validated through experimental analysis under various grid disturbance conditions, confirming its superior performance. It also gives the detailed analysis of DC offset, scaling errors along with design guidelines for enhancing its dynamic response.

The availability of Orthogonal Signal Generator (OSG) with PLL using second-order integrator, which influences the overall dynamical performance of PLL for solar PV grid integration. In OSG, at single stage, there are two output equations corresponding to orthogonal signals. But, sometimes due to imbalances the OSG leads to the loss of orthogonality at coupling point of OSG outputs and PLL. So, to tackle this, the proposed work introduces compensation of offset error (angle) at steady-state stage of PLL. Also, within the loop of PLL there is integration of moving average filter (MAF). For mitigating impact of MAF on stability of PLL alongside its dynamic response, phase-lead compensator has been designed. The experimental studies of proposed PLL not only offers excellent dynamic response but also ensure minimal fluctuations in PV power which will make it robust for single-phase grid applications [17].

The presence of DC-offset in grid signal for a PLL is an increasing concern because it is one of main causes behind oscillations in the estimated components. This paper presents a novel method for eliminating DC-offset in which there is deployment of delay signal cancellation (DSC) technique for synchronization. Moreover, there is deployment of variable length time delay (VLTD) in combination with DSC to make it more efficient PLL. The detailed results provide a discussion on the stability and small-signal model analysis. Also, there is analysis on optimal selection of gain values of controller. It also evaluates the performance on the basis of key metrics like: settling time, overshoot and peak of estimated frequency [18].

Hemant Saxena et.al [19] implemented cascaded Generalized Integrator (GI) to

enhance power quality of single-phase distribution network. Instead of single SOGI block, this study investigates the effectiveness of multiple cascaded SOGI for the mitigation of power quality issues, with aim to identify optimal quantity of cascaded GI. For performing this optimal selection, the system is tested up-to 10^{th} order GI. The proposed PLL has not been implemented on grid synchronization but also on estimation of fundamental load components for both open and close loop system. The performance is tested under various factors which includes modelling complexity of system, filtering abilities and response time alongside overall performance.

For the rapid grid signal positive and negative components detection José Matas et.al [20] designed a novel structure on the basis of GI. The GI's worked as GI based BPF, primarily use to provide orthogonal signal from grid side voltage signal. The structure utilized for proposed PLL composed of multiple cascaded structure GI-BPFs. The cascaded structure is capable enough to provide faster time response as compared to single GI-BPF by maintaining same bandwidth level. This multiple GI-BPF base structure is integrated with a PLL along with positive sequence detector which enables effective operation even during unbalanced voltage sags. The experimental results through simulations for Solar PV based power system operating in SRF and injecting power into the grid. A complte guide of the literature review is presented in Table 1.

Table 1: Summary of PLL advancements for solar PV grid integration under distorted/unbalanced conditions.

Ref. No.	Proposed PLL / Control Approach	PLL Type	Key Features	Application / Test Scenario	Main Outcom
[3]	Improved PLL (IPLL) with power feed-forward	Hybrid (SRF-based + Feed-forward)	DC-link & grid voltage incorporation; in-phase load current reference	GCSPV under unbalanced/distorted grid	Maximum grid power usage, improved PQ
[4]	Hybrid PLL (FLL + zero crossing detector)	Hybrid	Phase & frequency extraction;	Distorted grid	Near-zero THD

			real-time adaptability		
[5]	SRF-PLL with low voltage ride-through	SRF	Id control to limit inverter current spikes	GCSPV under faults	Spike limit 20–25%, improved fault tolerance
[6]	Non-linear SRF-PLL analysis	SRF	Handles oscillations under frequency variations	Nonlinear loads, poor filtering	Stable PLL under varying frequencies
[7]	Harmonic extraction PLL (no phase detector/oscillator)	Custom Harmonic PLL	Low overshoot, settling & computation time	Dynamic grid (freq./phase/ voltage jumps, harmonics)	Effective harmonic mitigation
[8]	Dual-layer filtering (DLF) + MSTOGI-PLL	MSTOGI	CDSC for unbalance cancellation	Unbalanced grid	99.5% phase accuracy
[9]	IPT-based PLL + resonant controllers	IPT-based	Delay error correction; harmonic suppression	Micro-grid with freq. variation & harmonics	Excellent dynamic/static performance
[10]	SRF-PLL with PO & LCL filter	SRF	Voltage regulation & MPPT integration	GCSPV single-stage inverter	Optimal under varying environment
[11]	Frequency-fixed SOGI-PLL	SOGI	Eliminates estimation errors under frequency drifts	Single-phase	Stable operation under unbalances
[12]	Dual TOGI-PLL + QT1-PLL hybrid	Hybrid	Adaptive filtering + rapid	Challenging grid synchronizati	Outperforms individual PLLs

			transient response	on	
[13]	SRF-PLL with derivative-filtered PID	SRF	Sequence separation with pre-filtering	Pre-filter + PLL integration	Reduced interaction, better stability
[14]	FFSOGI-PLL	SOGI	Simplified, stable under frequency drift	Unbalanced frequency drift	Ripple suppression, better estimation
[15]	EPLL in Synchronverter	EPLL	Sequence control for ripple-free injection	DER under unbalance	Ripple-free power injection
[16]	MNF-based Type-3 SOGI-PLL	SOGI	Eliminates phase error without delay	Disturbed single-phase grids	Superior dynamic response
[17]	OSG-PLL with MAF + phase-lead compensation	OSG-PLL	Orthogonality preservation	Single-phase PV grid	Minimal PV power fluctuation
[18]	DSC + VLTD-PLL	Custom	DC-offset elimination	Grid synchronization	Improved stability & estimation
[19]	Multi-cascaded GI-PLL	GI-based	Optimal GI order selection	Single-phase distribution	Improved PQ, filtering & response
[20]	Multi-GI-BPF PLL	GI-based	Fast positive sequence detection	PV under unbalanced sags	Faster response, stable injection

2.1 Research Gap Identified

The Solar PV integration with grid is a key for transitioning towards the more sustainable and renewable energy future. Such integration is much more essential in order to maximize the utilization of solar energy. It should also maintain the grid stability with enhanced reliability to electricity supply network. One of the key components for facilitating efficient integration is PLL which maintains the synchronization through feedback loop-filter (LF). The aim of this is also to improve steady-state capabilities of grid during adverse conditions. It is one of the traditional methods for maintaining the synchronization; but it suffers from problem of double frequency components which further cause its sluggish response in the presence of distortions from grid side. Due to this, the conventional PLL is not enough capable to track frequency and instability of grid accurately & efficiently under imbalances. In order to encounter mentioned problems associated with PLL, Enhanced Phase-Locked Loop (EPLL) comes into play which is an advanced control algorithm. It offers the improved performance, particularly in scenarios with grid voltage variations, harmonic distortions, and other challenging conditions. Some other techniques are used as pre-filter for filtering the unbalanced grid signal such as: SOGI based PLL, Cascaded SOGI based PLL, Dual SOGI, Moving Average filters, FF-SOGI based PLL. The current work intends to address power synchronization issues by conducting a rigorous and systematic evaluation of multiple control techniques.

3. Description of Broad Area

The integration of solar energy and the PV system is a sustainable approach. When integrated grid systems, it can harvest better results and improves grid efficiency in terms of energy output. However, the effectiveness depends solely on the parameters such as synchronization that is used in conjugation with the PLL system. Synchronization helps align phase angle and frequency of PV inverter output with grid voltage. Basically, PLL continuously monitor and input and output signals of grid side and inverter respectively. Thus, PLL systems helps to point out irregularities and helps to balance the input-ouput signals of gird and inverters. By this way the output frequency and phase angle of inverter to match with the grid. This is crucial for achieving synchronization. Continuous monitoring is achieved through a closed-loop process. Thus, under load fluctuating conditions the PLL systems ensures uniform energy output. Under normal adaptive conditions, achieving such uniformity in energy transitions using PLL system, is however challenging. However certain PLL variants such as SRF-PLL, DDSRF-PLL, SOGI based PLL and EPLL are put in place that have full tendency to minimize energy losses. An ideal PLL must be adjustable enough to adapt itself under dynamic grid conditions. It should also be efficient enough to mitigate the effects of harmonic distortion. As there is a tremendous advancement in solar PV technologies, a continuous development towards the designing of a sophisticated PLL algorithms at pre-filter and tracking stage is warranted.

4. Objectives of Research

1. To perm a systematic review of existing conventional PLL based techniques for Solar PV grid integration
2. Using MATLAB to design a novel PLL algorithm for efficient tracking of frequency and phase angle.
3. To investigate the performance of newly designed algorithm-based controller.
4. To perform a quantitative analysis of proposed with existing PLL based controllers on different metrics such as: settling time, frequency overshoot, peak phase error, etc.

5. Methodology

Below is the description of detailed step-by-step procedure carried out for the implementation of solar grid synchronization using the PLL technique:

Step 1: At initial stage there is initialization of system and perform simulation checks.
Step 2: Measure the grid voltage and solar PV inverter output voltage using sensors.
Step 3: Use the Clarke transformation for converting grid voltages to α (alpha) and β (beta) stationary frame components then into d-q rotating frame for easier processing so that extraction of phase angle is easy for PI controller due to one fixed and another rotator frame.

Step 4: By comparing phase of grid voltage with inverter voltage using a phase detector and compute phase error signal (difference between grid phase and inverter phase).

Step 5: Pass this phase error signal through a low-pass filter (LPF) to remove high-frequency noise and harmonic distortions.

Step 6: Use the filtered signal to adjust the frequency of a Voltage-Controlled Oscillator (VCO) to produce a synchronized reference phase signal that aligns inverter's output with grid's phase angle.

Step 7: There is adjustment of inverter output (voltage, frequency, and phase) to match the synchronized signals under various disturbances (e.g., sag, swell, or harmonic distortion etc).

Step 8: If the condition of Synchronization is achieved then inject solar PV generation to grid otherwise go back to phase error computation process.

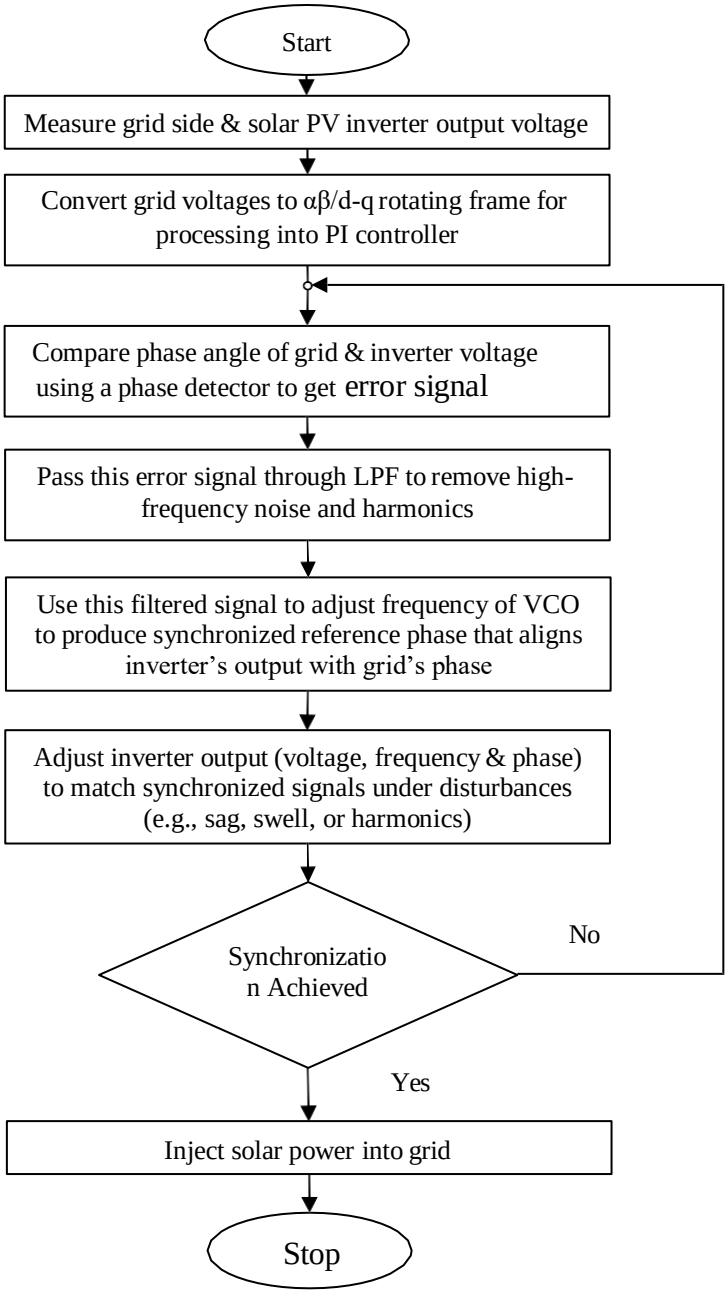
Start
Measure grid side & solar PV inverter output voltage
Convert grid voltages to αβ/d-q rotating frame for processing into PI controller
Compare phase angle of grid & inverter voltage using a phase detector to get error signal
Pass this error signal through LPF to remove high-frequency noise and harmonics
Use this filtered signal to adjust frequency of VCO to produce synchronized reference phase that aligns inverter's output with grid's phase
Adjust inverter output (voltage, frequency & phase) to match synchronized signals under disturbances (e.g., sag, swell, or harmonics)
Synchronizatio n Achieved
No
Yes
Inject solar power into grid
Stop

Fig.5.1. Methodology flow chart

6. Expected Outcome of the Research

The proposed PLL strategies are cornerstone for solar grid integration which provides the necessary synchronization between PV inverters with grid AC output voltage. The already available PLL's in literature are effective in many scenarios. There are various challenges associated with it like: weak grid conditions, harmonics, and faults. There are several researchers working on designing the adaptive, machine learning-based, and hybrid PLLs for further enhancing the reliability and efficiency of solar grid integration. Therefore, the necessity for development of advanced PLL techniques is much more in the context of grid-connected PV system. The proposed research has an aim to address the critical challenges associated with solar PV grid-connected systems under grid disturbances by developing advanced PLL algorithms and control strategies. Thus, obtained outcomes will help to improve performance and stability of PV systems. It also facilitates the broader adoption of renewable energy for electricity generation which further contributes in more resilient and sustainable power grid.

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by

Sumit Kumar Maitra

ABSTRACT

Currently, the integration of solar photovoltaic (PV) based generation systems with electrical grid is very important for expanding the use of renewable energy (RE) based generation system. One of the most critical components of this process is to achieve precise synchronization between solar PV inverter output with grid to ensure stable and efficient energy transfer. The Phase-Locked Loop (PLL) techniques are widely used for this purpose, as they enable continuous alignment of the inverter's output with grid's voltage, frequency and phase. This present research is focused on implementation of grid synchronization using the PLL technique by emphasizing on operational flow and key components.

As per existing literature, number of PLL techniques such as: Synchronous Reference Frame PLL (SRF-PLL), Second Order Generalized Integrator (SOGI) based PLL, Third Order Generalized Integrator (TOGI) based PLL and other enhanced PLL have already been proposed by number of researchers and their performance is also tested under non ideal grid conditions like: "voltage sags & swells, frequency variations, DC offset and harmonic distortions". The improvement in performance has been validated through improved dynamic response via transient parameters like: "rise time, settling time, peak time, overshoot and peak phase error" etc. The process of synchronization also includes the continuous monitoring of grid conditions to maintain stability and reliability. This enables the efficient injection of solar power into the grid even under fluctuations in grid either from grid side or load side.

In this thesis, novel enhanced PLL based synchronization method is proposed to ensure the robust and reliable solar PV grid integration which would further contributes to improvement in grid stability and power quality via renewable energy adoption. For the analysis of results, the simulation process is carried out in Matlab. The improved dynamic response obtained through simulations and analysis in terms of above-mentioned transient parameters will reveal the superiority of proposed controller.

Key Words: Grid Disturbances, Phase Lock Loop, SOGI, Solar PV Integration, Synchronization

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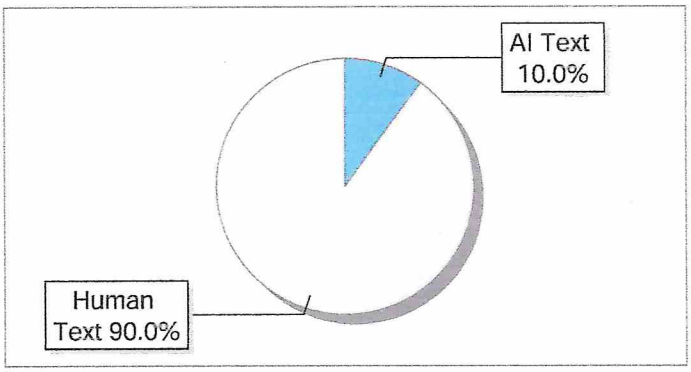

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